



Excimer Lasers for IFE with Raman and Brillouin Staged Boosting

ARPA-E Workshop

March 7, 2023

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CEO, FOUNDER
XCIMER

XCIMER
ENERGY CORPORATION

Xcimer team has decades of experience in lasers, fusion, and high-energy engineering



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A world expert in pulsed
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Our Xcimer team includes experienced collaborators and advisors

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Team at Xcimer design review Jan 13th 2023

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A National Team for excimer IFE including expertise from renowned institutions

LABORATORY FOR
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UNIVERSITY OF ROCHESTER

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Cory Stansbury, Edward Lahoda



Kevin Robb, Jeff Ullreich



Allison Christopherson, Omar Hurricane, Max Tabak



*Dan Gordon, Frank Hegeler, Matthew Myers,
Joe Schumer, Matthew Wolford*



Akintunde Akinwande



John Kline, Mark Schmitt



*Christopher Dandeneau,
Brenda Garcia-Diaz*



Neil Alexander

We Are Revolutionizing Laser Fusion

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***Our lasers will scale to 10s of MJ
with flexible illumination geometry and spatio-temporal pulse shaping***

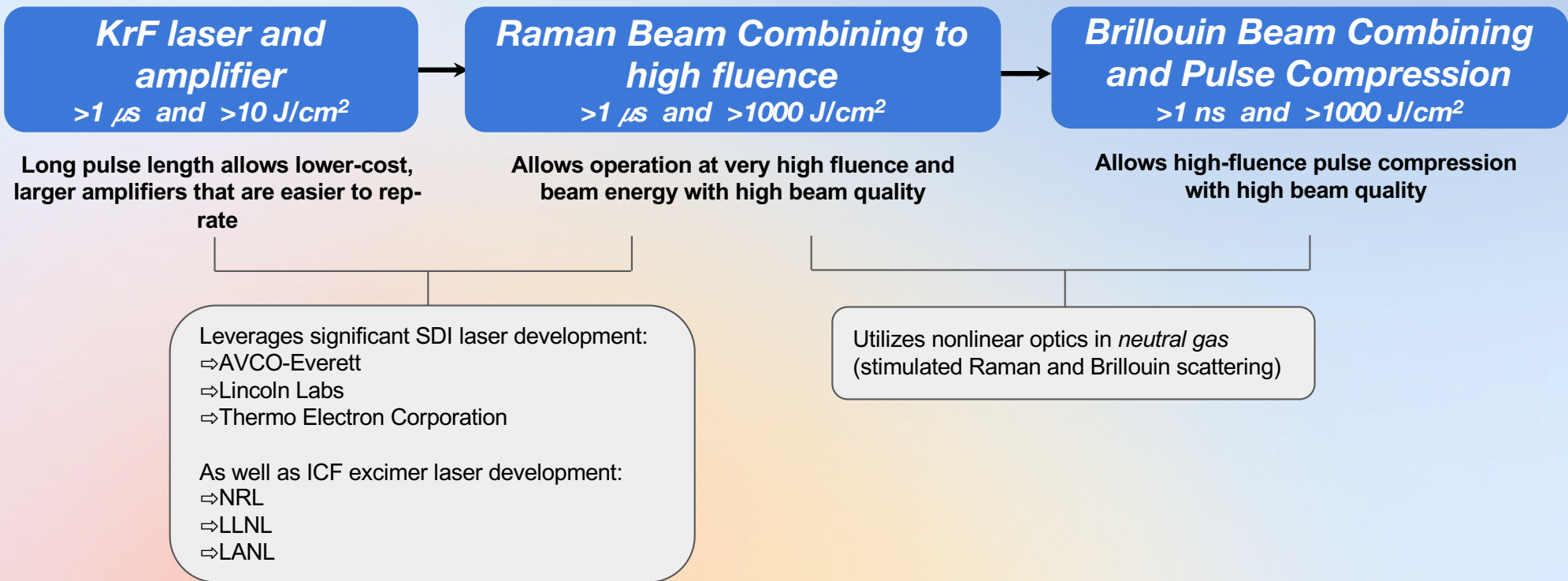
**This allows the adoption of
ever simpler and more
robust targets**

**This allows the adoption of the HYLIFE
chamber design and the mitigation of
its outstanding challenges**

**This is the fastest and lowest-risk realistic
path to laser-fusion power on the grid**

How will we scale to 10s of MJs?

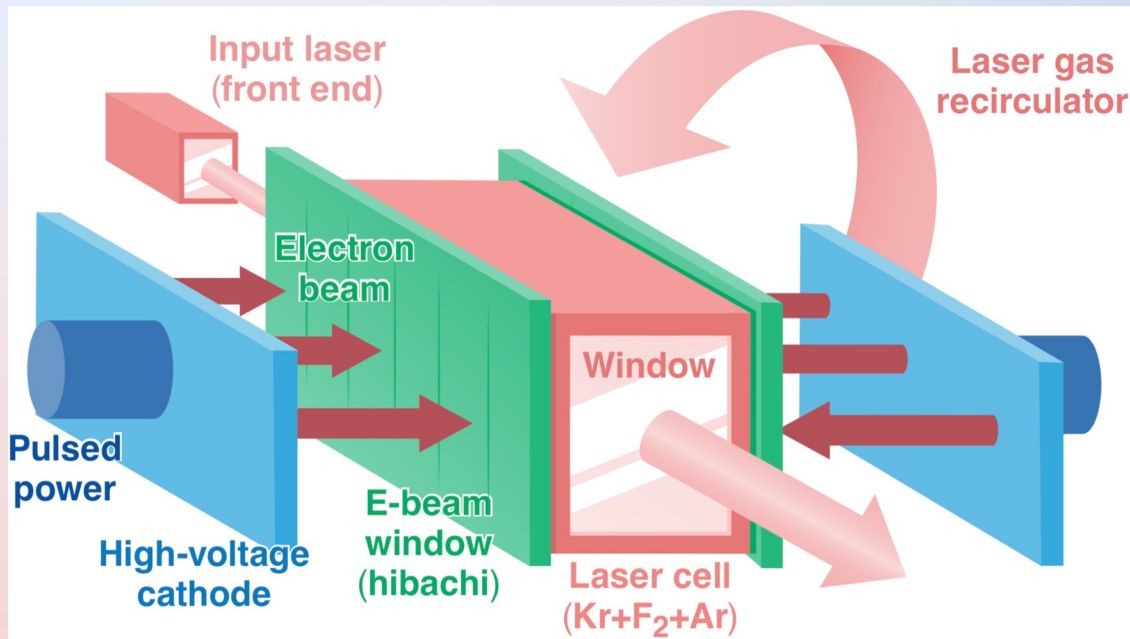
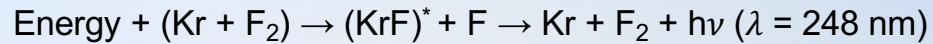
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Flexible, modular, and affordable multi-MJ laser systems for IFE are made possible at Xcimer by staged NLO based spatio-temporal pulse-shaping and beam combining

Basic elements of a KrF laser

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| | |
|----------------------------|-----------------------------|
| Short upper state lifetime | ~3 ns |
| Low saturation fluence | ~2 mJ/cm² |

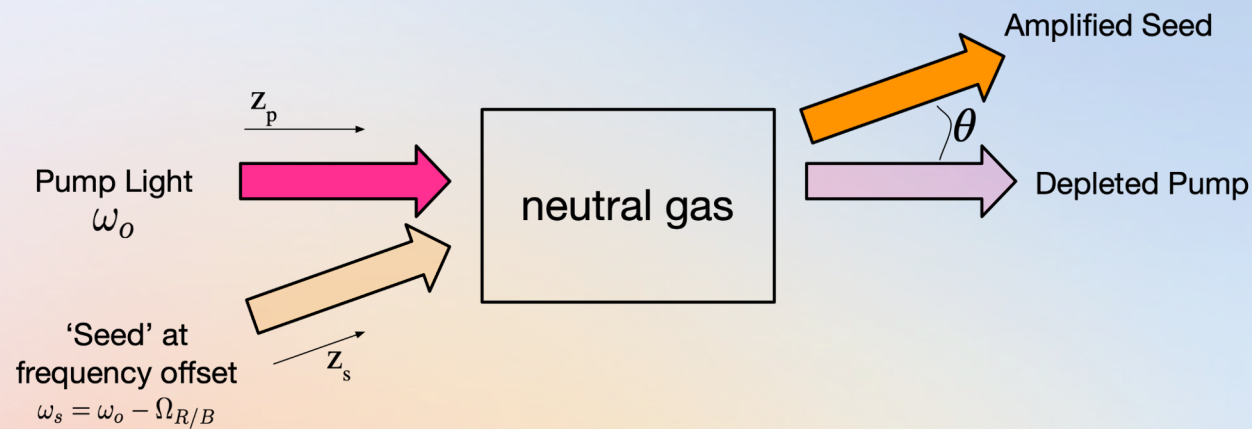
→ NOT a storage laser, must be continually pumped

| | |
|---------------------------|---------------------------------|
| High saturation intensity | ~1 MW/cm² |
| Output fluence range | 3 to 15 J/cm² |
| Pulse length range | 100 ns to 3 μs |

→ Optical energy must be **"pulse compressed"** for laser fusion

Beam fluence amplification and temporal compression achieved using nonlinear optics

⇒ Stimulated Raman and Brillouin Scattering



Two slight frequency offset laser beams interact with longitudinal excitation of gaseous medium:

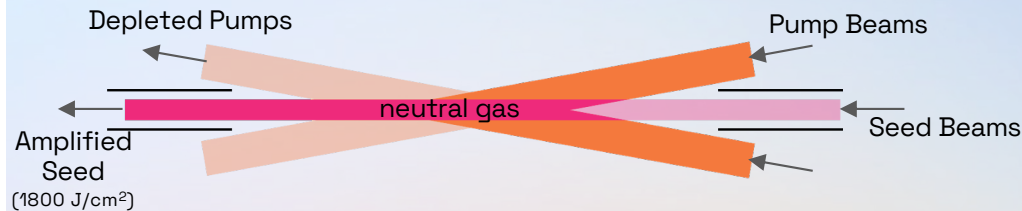
Brillouin - acoustic phonon

Raman - molecular vibration / rotation

Feedback mechanism produces a large driven 'seed' which depletes energy from the 'pump'

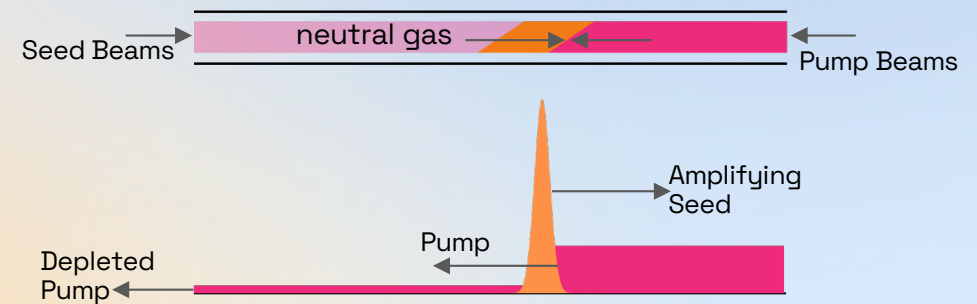
Efficient energy transfer from pump to seed

Beam Combining



Pulse Compression

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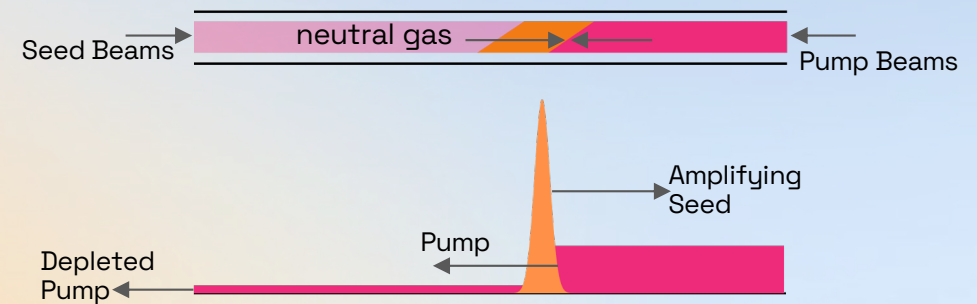
- Raman and Brillouin amplifiers transfer energy from pump to seed via interaction with *neutral gas @ 1 atm*
- ⇒ **Gas** cell amplifiers can handle *much* higher energy fluences than **glass** and cannot be easily damaged
 - ⇒ Preserves Phase
 - ⇒ Very little energy deposition into amplifying medium (10^{-3} for SRRS, 10^{-6} for SBS)

Beam Combining



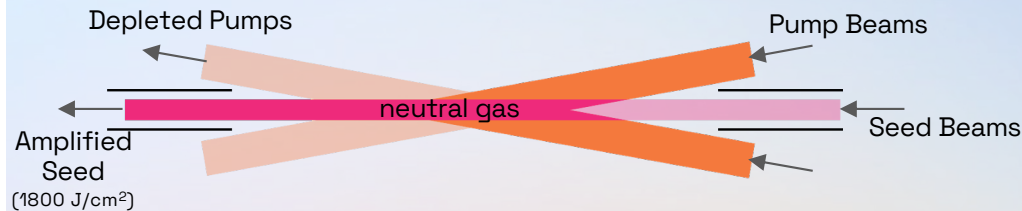
Pulse Compression

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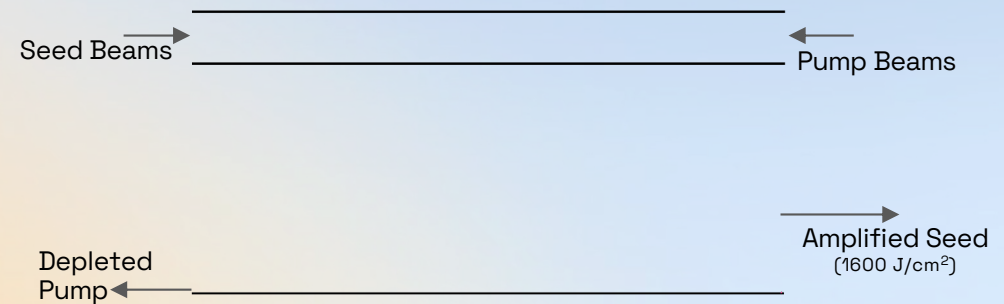
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Beam Combining



Pulse Compression

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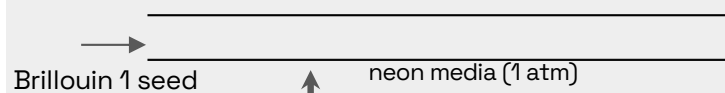


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Putting the pieces together

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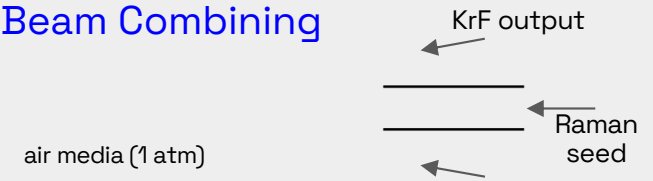
Brillouin 1 Compression



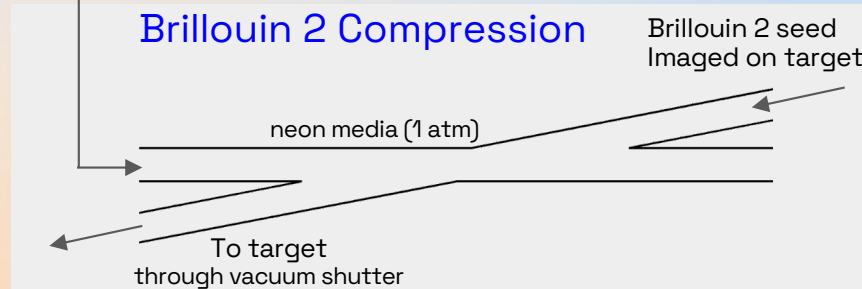
Total beam area for
6 MJ on target: **0.5 m²**

Total beam area for
12 MJ on target: **1 m²**

Raman Beam Combining

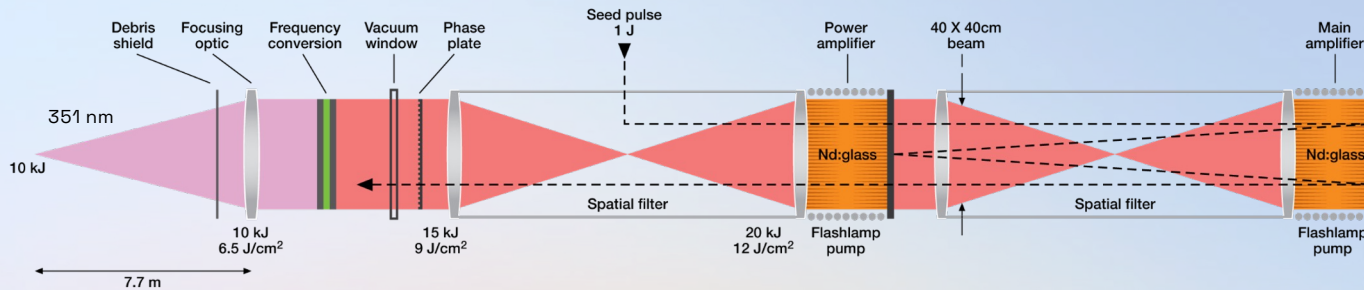


Brillouin 2 Compression



⇒ No glass optical elements see damaging fluences

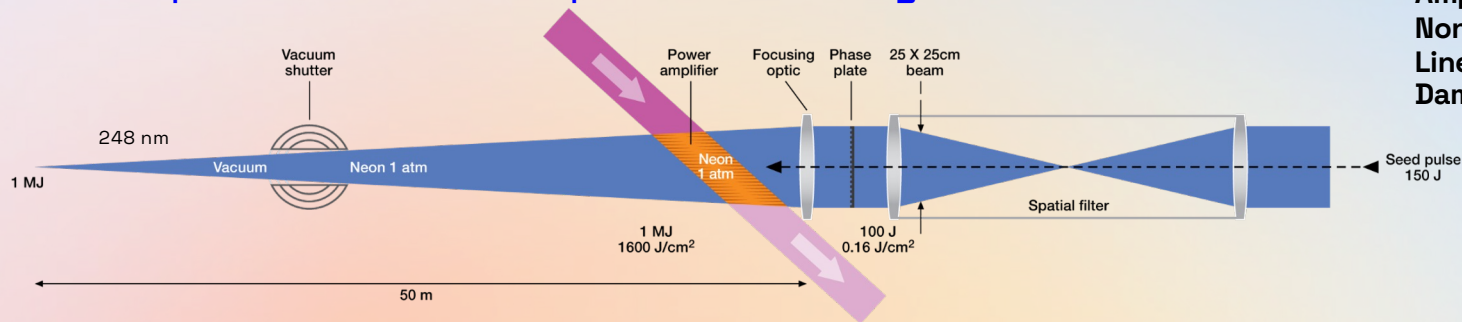
Power amplifier *before* final optics: NIF system



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Amplification factor: 2×10^4
 Nonlinear Index: $3.5 \times 10^{-16} \text{ cm}^2/\text{W}$
 Linear Index: 1.5
 Damage Threshold: 5-10 J/cm²

Power amplifier *after* final optics: Xcimer system



Amplification factor: 10^4
 Nonlinear Index: $6 \times 10^{-21} \text{ cm}^2/\text{W}$
 Linear Index: 1.000065
 Damage Threshold: 58 kJ/cm² (@18ns)

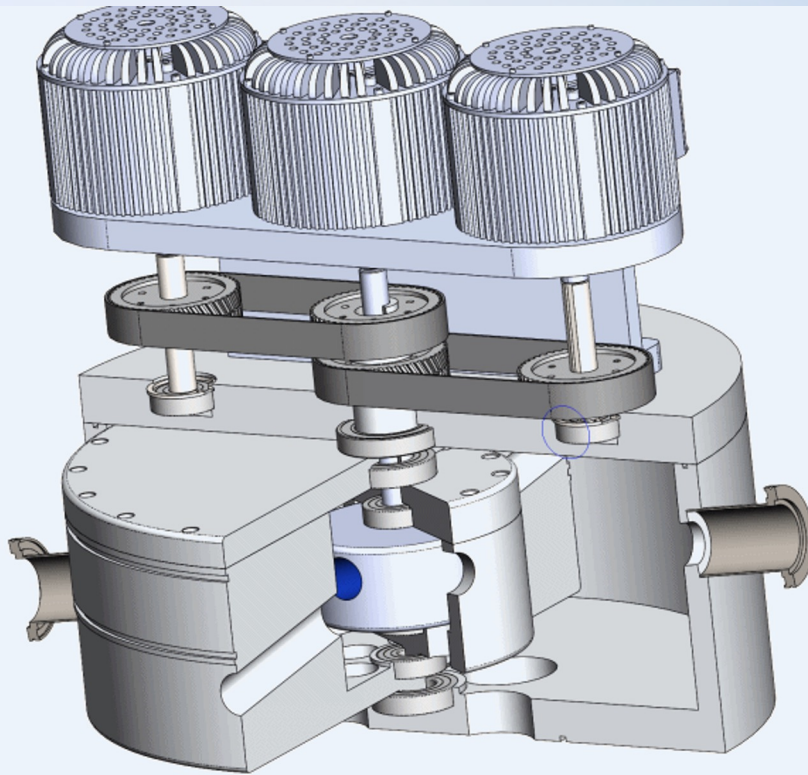
Don't break glass, have a gas

Near-diffraction-limited performance possible due to:

- ⇒ Very low linear and nonlinear refractive indices
- ⇒ 10^{-6} fractional energy deposition into medium
- ⇒ Close adaptive optics (AO) loop through vacuum shutter

We propagate high-fluence laser pulses from gas to vacuum *without a window*

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***Eliminate the need for windows
don't break glass, have a gas***

Xcimer's baseline IFE target design is driven by 12 MJ

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Developed with LLE through D.O.E. INFUSE award, expansion of effort to include LLNL, LANL

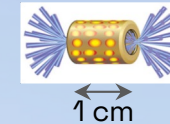
Uses the same proven “hotspot ignition” physics as NIF, here adapted for two-sided illumination

Implosion symmetry achieved with shaped beams, shimmed target, and electron thermal conduction

More generally:

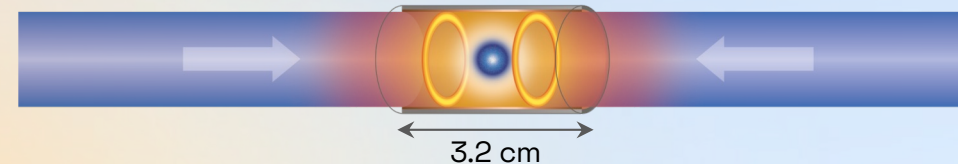
High-energy design space leads to higher adiabat, lower compressions, looser tolerances, lower rep-rate, and robust implosions significantly exceeding ignition criteria

NIF (2 MJ):



Xcimer (12 MJ):

First Pulse Indirect Drive



Subsequent Pulse(s) Direct Drive



HYLIFE chamber has advantages that mitigate fusion challenges

Waterfall of FLiBe: coolant, x-ray/debris absorber, neutron moderator, and tritium breeding material all-in-one

Liquid FLiBe directly protects first wall from x-ray/debris and 14 MeV neutrons

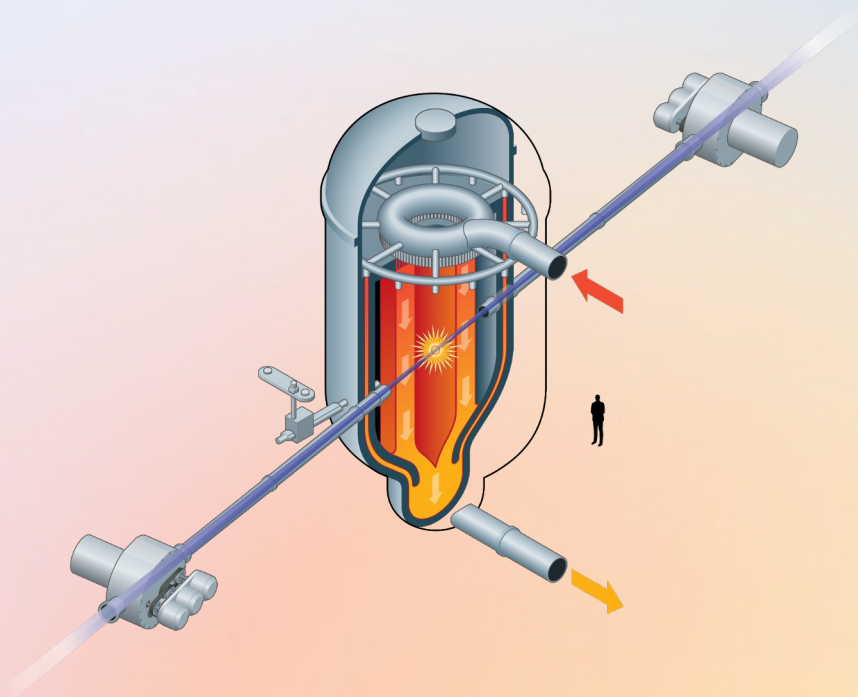
➤ *Key advantage over other fusion approaches*

No “first wall problem” - structural wall can last entire 40-year-design lifetime of the plant.

Significantly lower activation and waste production compared to conventional DT fusion approaches

Mitigating challenges of HYLIFE-2:

- Only 0.25 - 1 Hz rep rate
- Large 50 m stand-off
- Only two beam ports ~10 cm across
- No jet oscillation required
- 30 m of 1 atm gas protects final optics



First Xcimer facility will demonstrate critical laser elements - starting in Q3 2023

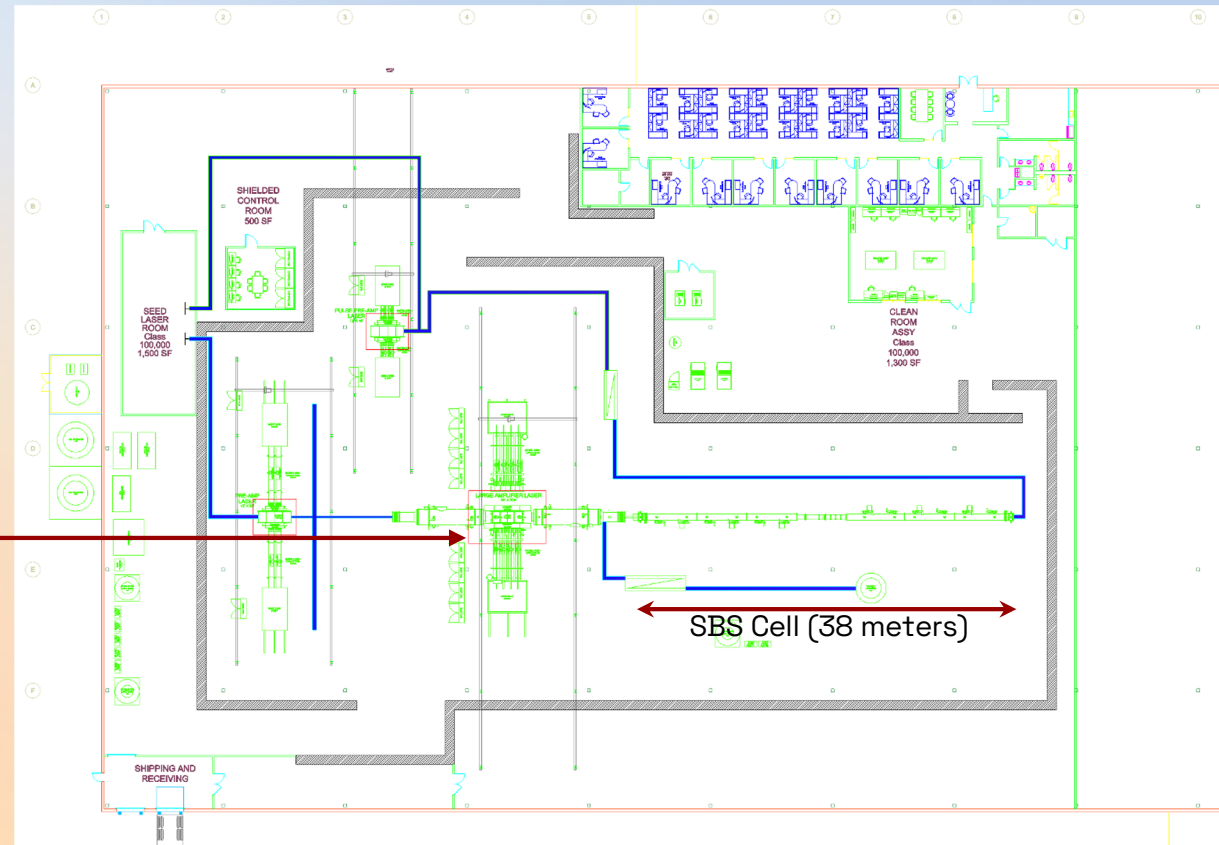
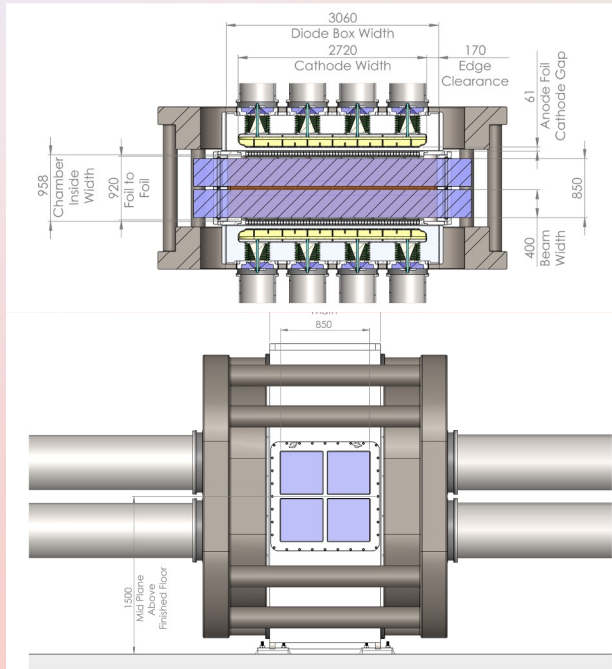
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⇒ High temporal compression low-pressure SBS

⇒ Imaging and AO through SBS, form target illumination pattern

⇒ Vacuum shutter

⇒ Arbitrary waveform generation and STUD pulses through SBS



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| Xcimer performance goals | Where we are today | IFE Goal | <div>Comments</div> <div>XCIMER</div> |
|---|--|--|---|
| Pulse energy (single KrF amplifier) | 10 kJ (LAM at LANL) | 500 kJ to 5 MJ | Multiplexing and shorter pulse (≤ 250 ns) limit size of single amplifier. Removing these constraints allows much larger units, though challenges remain (eg. kinetics uncertainty and F_2 burnup, cathode segmentation to avoid TTI). |
| Repetition Rate | 5 Hz (Electra) | 0.25 - 1 Hz | Low rep rate relaxes many requirements, including required total shot lifetime |
| KrF efficiency | 7% (if using solid-state pulsed power demonstrated separately) | 9% - 10% | Longer pulse, larger size, higher voltage, and lower current amplifier with expanding extraction geometry leads to improvements in efficiency, in principle, over what has been demonstrated for multiplexing. However, long-pulse kinetics uncertainties remain as well as segmented cathode design - Xcimer to retire risk with 100 kJ KrF prototype. |
| SBS pulse compression Efficiency, Compression Ratio, Energy (for single SBS amplifier stage and beam) | >90%, 60:1, >Joule (in separate experiments) | >90%, 100:1, ~MJ | Scalability of SBS will be demonstrated on Xcimer's first testbed facility |
| Target Gain | 1.5 (NIF) | 200 | High driver energy, significantly exceed ignition criteria. Adiabat 3-4, imploded mass 15-20 mg, laser energy 8-12 MJ |
| Foil lifetime | 150k shots (NRL) | 30M shots (1 year @ 1 Hz) | 150k shot failure wasn't due to foil. Going to lower current, higher voltage, larger AK-gap, and solid state switches will improve foil lifetime. Possible hot swap with extra amplifier unit on the floor. Investigate different alloys (Be, graphene, metalized polymer, etc..) |
| Capacitors and Solid State Switch lifetime | 500M shots (L3-Harris during Electra program) | 1B shots (30 year @ 1 Hz) | Cathode test stand at NRL with solid state switches, 10M shots. L3-Harris demonstrated foil-film all-polypropylene caps with solid state switches for 500M shots |
| <div>Solid state switch (current, voltage, di/dt)</div> <div>Small (~1 cm)</div> <div>Large (~10 cm)</div> | <div>5 kA, 45 kV, 40 kA/μs (10M shots at NRL)</div> <div>100 kA, 50 kV, 20 kA/μs (500M shots at L3-Harris)</div> | <div>100-200 kA, 25-50kV, 200 kA/μs</div> | Lifetime already sufficient for IFE. Need to lower cost and develop supply chain. Higher di/dt can reduce cost of magnetic components. |

New Optical Ultrafast Thomson Scattering Diagnostic (OUFTS) will reveal complex LPI dynamics and open the door for active control

Optical Ultra-Fast Thomson Scattering diagnostic (OUFTS)

Measure EPW and IAW dynamics with 0.1 ps resolution and long record length > 100 ps)
Time Bandwidth Product 1000-10000

Two Key Missing Element

Optical Arbitrary Waveform Generation to produce STUD pulses and Broadband, space-time controlled Pumping of SBS

OUFTS diagnostic capability critical for fundamental understanding of LPI physics and for LPI mitigation and control

OUFTS diagnostic crucial for the successful implementation of the STUD pulse program. (Spike Trains of Uneven Duration and Delay)

Arbitrary Waveform Generation to produce STUD Pulses in SBS cell and On Target

Control LPI, Adapt, Learn, optimize laser pulse → Maximize Target Design Phase Space and mitigate uncontrolled risk

Essential characteristics of OUFTS:

- Use high frequency optical probe pulses with a broader bandwidth than the nonlinear plasma modes being probed.
- For ~100 fs resolution, stretch and temporally chirp the probe pulse.
- Encode temporal collective plasma response into the spectrum of the Thomson scattered pulse.
- Decode the plasma dynamics now encoded in space and read out in time-integrated mode.
- Determine the required “local” (i.e. spike) and overall pulse bandwidths for different laser-plasma interaction parameter regimes.
- Determine the rate of the required chirp and the temporal duration over which a single pulse can be used to probe complex LPI dynamics as envisaged in the STUD pulse program.

Improvements in solid-state switch technology and supply chains needed for cost reduction and commercialization

Solid State Switch Technology Development

- Solid-state switches are needed to provide adequate reliability and lifetime for a commercial power plant
- Large area devices limited to ~ 20 kA/ μ sec di/dt and require saturating magnetic assist
- Several potential paths for development
 - Application of demonstrated small-area inter-digitization techniques to larger area devices
 - Improved concepts for light-activated triggering, e.g. via 2D VCSEL arrays
 - Improvement of fabrication and scaling of wide-bandgap (SiC) devices
- Supply chain development is needed based on expected volumes for FOAK plants and beyond

Capacitor Technology

- Scale up production capability
- Possible improvements to winding techniques, reproducibility, dielectric materials, impregnation materials, foil edge treatments, terminating & packaging
- Goal is to improve lifetime and increase energy density

Magnetic Tape Coating Improvements

- Tape-wound cores are needed in many pulsed power topologies for IFE
- Cores are wound with polymer film and/or kraft paper, precludes ability to anneal post-winding
- Heat-compatible coatings have been developed for transformer and other power applications, allows post-winding anneal for maximum flux swing, but insufficient turn-by-turn insulation strength
- Improved heat compatible coatings for magnetic tape could result in mass and volume reduction in several components

Longer pulse lengths lead to less foil stress

During the HAPL program (2000-2009), NRL's KrF laser Electra achieved

- 90,000 continuous shots at 2.5 pulses per second (pps)
- 150,000 shots on the same pressure foil

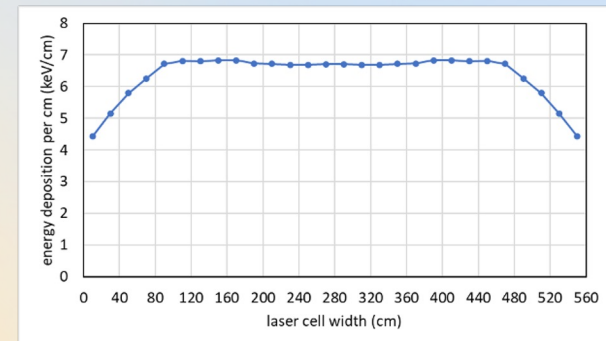
with a 1 mil (25 μm) thick stainless steel foil, operating at a diode voltage of 500 kV.

Main limitation for NRL's Electra laser: Spark gap type pulsed power components that produced higher rate of "misfires" or inconsistent diode voltage pulses after 10,000s of shots.

The following changes are made to significantly improve the robustness of the Hibachi/pressure foil design:

- Use a pulsed power system based on solid state switches (diode voltage pulse is very repeatable without misfires)
- Increase the foil thickness from 1 mil (25 μm) to 2 mil (50 μm) stainless steel
- Increase the electron deposition efficiency into the laser gas to 88% by increasing the diode voltage from 500 kV to 2 MV
- Decrease the average diode current density from 33 A/cm² to 11 A/cm², which will significantly increase the distance between the cathode and the stainless steel pressure foil
- Decrease the laser gas pressure from 1.36 atm to 1.0 atm (less stress on the stainless steel foil)
- Xcimer will work with NRL to design and test the next generation hibachi

⇒ *Future tests on Electra*



1-D energy deposition of a double sided 2 MeV electron beam into a 88.2% Ar, 11% Kr, and 0.8% F₂ laser gas at 1 atm, using 2 mil thick stainless steel foils.

Improvements in coatings and window materials can increase efficiency

Optical coating technology development

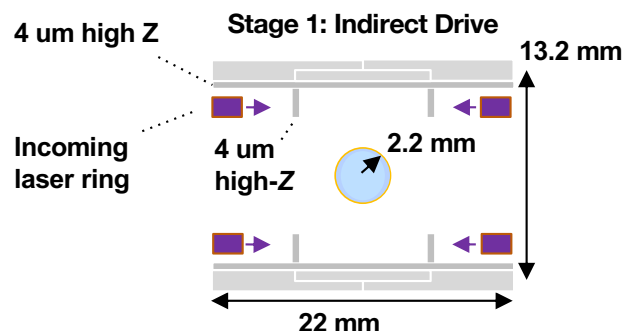
- While Xcimer will operate with more damage margin than NIF, optical coating performance (esp long-pulse/high-fluence pump coating lifetime) is still a significant technical and economic constraint.
- Pump fluence and shot lifetime will be a critical trade for FPP and NOAK plant designs.
- *Research Tasks: Develop coating test capability and partner with coating suppliers to characterize and improve the coating design space, including use of MgF_2 and CaF_2 window material at ~ 40 cm beam size.*
- *FPP/NOAK Metrics: Full aperture coating shot lifetime at maximum fluence.*

Low-cost large-aperture pump optics supply chain development

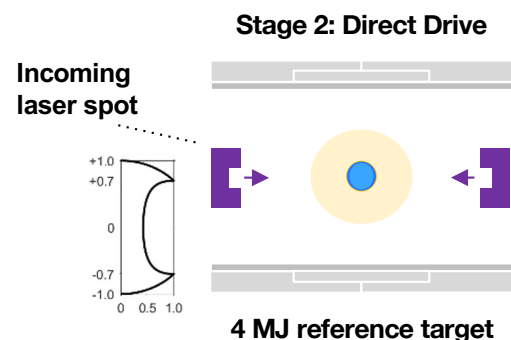
- Optics handling KrF output / Raman pump ($>1\mu\text{s}$ pulse length) are biggest optics cost driver.
- SRS/SBS preserve seed phase, permits significant relaxation in pump optical element unit cost driver (surface figure).
- Supply chain for high-volume/low-cost/modest-quality sub-meter-class optics is underdeveloped.
- *Research Tasks: Work with leading optics vendors to develop an updated cost model and roadmap for Raman pump optics production.*
- *FPP/NOAK Metric: Plant total pump optics cost/volume curve.*

Backup

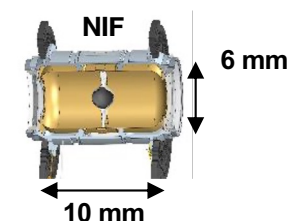
Recent INFUSE award was used to stand up sims of a baseline 4 MJ Hybrid target, and demonstrate features of indirect and direct drive*



- Initial impulse is low energy, and aimed at zeros of Legendre P2 for a LGF hohlraum ~ NIF, with a case-to-capsule ~ 3
- X-rays generate plasma atmosphere
 - No laser imprint, fewer seeds of instability**
 - No shine through, predictable first shock**
- DT fuel is put on the same effective adiabat as successful shots at existing facilities, 5-6, to mitigate instabilities
 - No need for Fermi degeneracy or finesse**



- Bulk of energy delivered directly in ring-peaked laser spots that follow the implosion/zoom at 10^{15} W/cm² or less, very efficient
- Laser coupling 6x greater than HyE or more (150 kJ vs 25 kJ)
 - CBET is suppressed by geometry, laser, and materials**
- Volumetric heating of corona and conduction zone provide near-symmetric pressure, adequate implosion symmetry
- Residual modes adjusted with laser profile and capsule



Low mode symmetry is primary risk by construction, with multiple factors to mitigate

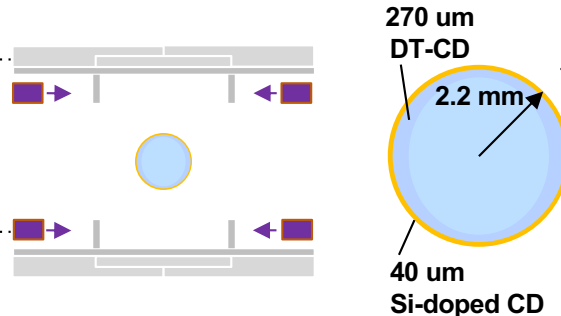
Innovations in fabrication and laser physics are critical to success

Outer cylinder/sabot of FLiBe or LiPb

provides strength, thermal inertia, and a shield to IR with no consequences to waste stream outside of a thin high-Z coating, if used. Parasitic waste from indirect drive is reduced a factor ~100. Efficiency in stage 1 is not important, so, materials choices are flexible.

KrF laser wavelength is short, 248 nm, to increase absorption and suppress LPI. Multiple lines can be used to increase the effective bandwidth. ArF could have concomitant benefits, and will be a subject of study.

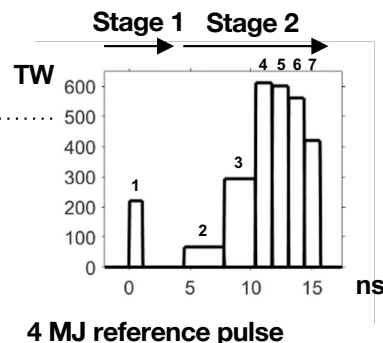
Laser architecture enables 1 to 12 discrete segments in time, each of which has an actively controlled spot. Approach enables an incremental version of zooming, and might be compatible with an in-line version of shock or fast ignition, which are also areas of study.



DT-wetted foam requires very little time to layer, reduces fuel age and inventory, and can be shaped to correct systematic asymmetries in drive, if needed.

Si-doped CD shells are known to suppress LPI and hot electrons, and are much easier to make than high density carbon HDC diamond. Details can be changed based on factors like activation, or aspects of system integration.

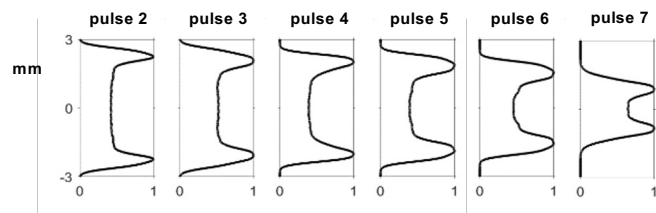
Radius and thickness are much larger than HyE, 2x or more, but implosions reach the same pressure at low IFAR. Lawson parameter and margin are doubled, and sensitivities to flaws are lessened. Energetic hots are ranged out. Implosions at OMEGA in a similar parameter space obtain a high fraction of expectations, 1/3 to 1/2 of 1-D, despite small scale.



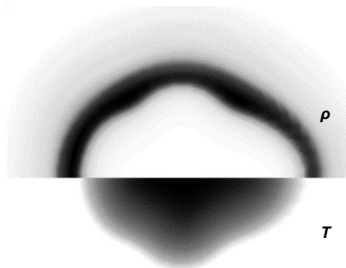
Process for tuning is familiar to indirect drive, and synergistic with rep rate

Hybrid targets also have adequate implosion symmetry in simulation, and show scale is highly beneficial to margin*

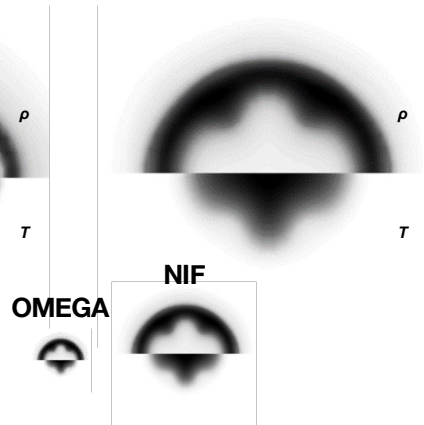
Optimized laser profiles



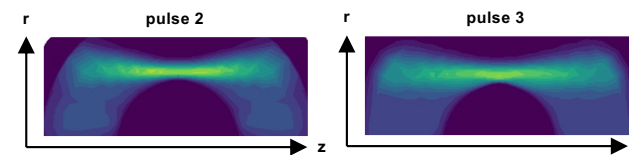
Hybrid with alphas ON peak CR at 15.74 ns



Hybrid with alphas OFF peak BR at 15.86 ns



Local Total Intensity versus position



- 4 MJ KrF reference design relative to NIF HyE:
 - Stagnation pressure reproduced at adiabat 5-6
 - Imploded mass (and areal density) exceeded by 12x (3x)
 - Maximum gain exceeded by factor of 30-36
 - Physical scale larger by 2.3x
 - Lawson and alpha-heating metric $\chi \sim 2x$ larger
- Target ignites if no-alpha yield > 1/10 of 1-D ($\chi \sim Y^{0.3}$)
- Hotspot $\rho R > 0.3 \text{ g/cm}^2$ even if 9/10 of mass is dudged
- Velocity (laser power) exceed threshold to ignite by 1.3x (1.5x)
- Target goes off going in at modest CR ~ 19

Xcimer will leverage all of the findings of OMEGA and NIF

- Targets will be robust to instability, also to chamber IR, glint, shine through, condensation, injection, etc.
- CBET and LPI will be avoided, or targets will be redesigned
 - CBET is bypassed by construction (geometry of laser and target, and absorption characteristics)
 - LPI risks are expected to increase with scale, but decrease with mid Z dopants, laser wavelength, low intensity drive
 - Tests of direct drive at NIF have shown promise, even at intensities \sim few 10^{15} W/cm² at 351 nm
 - Relatively speaking, Hybrid targets will be larger, but use several features to reduce risk
 - High average Z
 - KrF or ArF, 248 nm or 192 nm
 - Low intensity drive
 - High(er) quality laser spots
 - Arbitrary waveform generation and Spike Trains of Uneven Duration and Delay for active LPI control
- Alternative concepts will be internally peer-reviewed, address risk factors, provide plan B, C, etc.

Baseline strategy is hot spot ignition, and to delay the technical and LPI issues \sim FI or SI